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Chapter 26 – Active Monitoring Using Submarine Cables—Leveraging Offshore Cabled Observatory for Passive Monitoring

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Active Monitoring using Submarine Cables

–Leveraging Offshore Cabled Observatory for Passive Monitoring–

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ABSTRACT

Eight seafloor observatories installed in Japanese water. Passive monitoring by these observatories have revealed a number of qualities that include detailed micro-earthquake activities before and after plate-boundary earthquakes, the existence of micro-tsunamis, the capability of early detection of tsunamis, the importance of seafloor geodetic observations, etc. These new findings were brought by passive, real-time and continuous time series of earthquake and tsunami records acquired on the seafloor. Recently, our knowledge about earthquake source mechanisms has revealed the possibility in the detection of spatiotemporal changes in physical properties that may occur at inter-plate boundaries and active seismic surveys found reflection amplitude difference at seismically inactive plate boundary or possible seismic asperities. We propose that the detection of such physical property changes becomes possible when we combine seafloor observations and active seismic sources dedicated to precise monitoring of reflection amplitudes at plate boundary interfaces.

INTRODUCTION

Japan has started installing their cabled observatories for disaster mitigation purposes since 1978. The Headquarters for Earthquake Research Promotion in the Ministry of Education, Culture, Sports, Science and Technology (MEXT) has advocated in 1996 to install cabled observatories for earthquake and tsunami monitoring purposes at least in five sea areas (Figure 1). The advantages of utilizing cabled observatories have been reported as 1) improvements in the detection of micro-earthquakes in seismogenic zones in terms of their magnitudes and locations (Watanabe, et al., 2006a), 2) improvements in the real-time detection of tsunamis with a leading time before their arrival to the coast (Matsumoto and Mikada, 2005), 3) detection of long-term seafloor crustal deformations (Mikada, et al., 2006), etc. The deployment of earthquake monitoring systems in the offshore has been proven efficient in the past for studying earthquakes taking place mainly in the offshore.

Recently, seismological studies of earthquake source mechanisms indicate: (1) seismic asperity of a fault may break more than once at the same area of the fault in a different earthquake cycles (Nadeau and McEvilly, 1999; Nagai, et al., 2001; Hirose and Hirahara, 2002), (2) rupture process can be complex and a wide variety of earthquake phenomena is caused not only by the heterogeneity such as asperity, but also from an intrinsic property in the fault system (Hirose and Hirahara, 2002). In the past, passive monitoring, micro-earthquakes and geodetic measurements have been the main target of observations but the physical properties of fault planes can not be directly estimated through the passive observations unless we find a way to monitor properties directly. A reflection profiling, i.e., an active method, before and after a megathrust earthquake that took place in

2003, showed that there were changes in reflectivity and seismic velocities at the location of its hypocenter (Tsuru, et al., 2005). This finding implies that the active schemes could be taken to obtain time-variant physical properties of fault planes. Therefore, it is important to resort to active schemes for acquiring physical properties along with the passive monitoring schemes. The integration of these methods should be of the most preferable way for further understanding of earthquake phenomena.

We propose (1) passive monitoring of seismogenic zone for precise micro-earthquake locations, source mechanisms, and continuous geodetic monitoring of seafloor deformation, and (2) active monitoring using multidisciplinary sensors for acquiring changes in physical properties in the vicinity of plate interface in seismogenic zone. We would like to demonstrate scientific results from our past studies both in earthquake and tsunami monitoring and to show the necessity of further active monitoring schemes. Our discussions would also show the necessity of offshore observations for understanding earthquake generations and continuing research and development of multi-purpose observation sensors for future earthquake monitoring systems.

JAPANESE CABLED OBSERVATORIES

Japanese islands are located at the intersection of four plates (Figure 1). The collision of plates causes earthquakes at their boundary every several tens to a few hundred years. Figure 1 represents eight earthquake monitoring cabled observatories, one of which is a test bed for sensor and engineering developments in the Japanese water (Hirata, et al., 2002). Since the first cabled observatory was installed in 1978 in off Tokai region (annotated as “a” in Figure1), the other seven observatories are successively deployed for monitoring future megathrust earthquakes and associated tsunamis. These systems mainly equipped with either broadband or highly sensitive seismometers and water pressure gauges are in operation regularly and all acquired data are telemetered in real-time to the broad community of researchers, the Japan Meteorological Agency (JMA) and to the other research organizations through the High Sensitivity Seismograph Network (Hi-Net) system of the National Research Institute for Earth Science and Disaster Prevention Center (NIED) (Obara, 2002). For further research in earthquake seismology or regional tectonic studies, passive monitoring of earthquake activity in the seismogenic zones at plate boundaries is currently the mostly practiced approach. During the past decades of system development and stacked experience to use submarine systems, the number of systems is not sufficient enough to cover the high-risk region of megathrust earthquakes. This is because the most critical problem in the installation of cabled seafloor observatories is well known as enormous cost of deployments (Asakawa, et al., 2002).

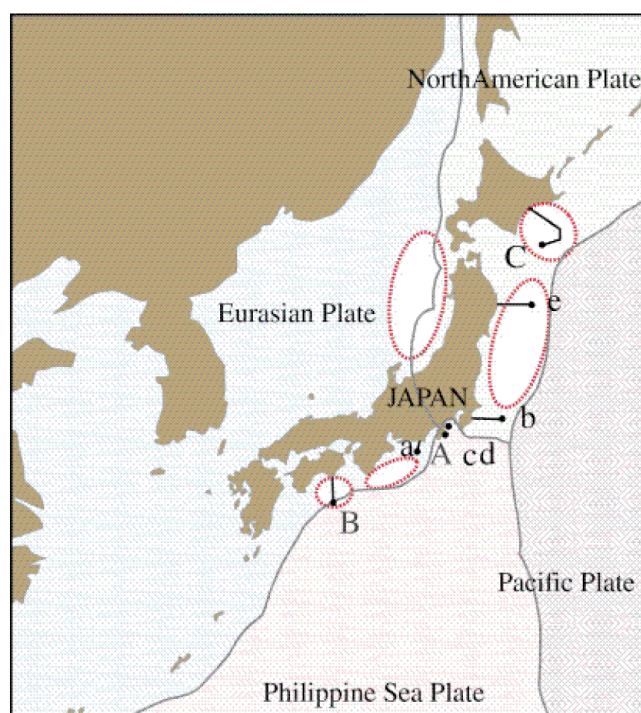


Figure 1 Cable systems, areas of special measurement act, Japanese islands. Eight cabled observatories around Japan for earthquake monitoring and engineering developments (Hirata, et al., 2002). They are a) JMA Off-Suruga, b) JMA Off-Boso, c) ERI East Off-Izu Peninsula, d) NIED Sagami-Trough, e) ERI Off-Sanriku, A) JAMSTEC Hatsushima (Engineering Development Site), B) JAMSTEC Off-Muroto, and C) JAMSTEC Off-Tokachi-Kushiro systems. Circled water areas were advocated by the Headquarters of Earthquake Research Promotion that the real-time observations are necessary for future potential of catastrophic earthquakes.

SCIENTIFIC ADVANCES BROUGHT BY THE CABLED OBSERVATORIES

Earthquake Studies

The installation of seismometers in the offshore has been well appreciated by seismologists for locating seismic events taking place at the plate boundaries (Hino, et al., 1996 for example). It has been shown that earthquakes of much smaller magnitudes were observed after the installation of a cabled observatory in the southwestern off Hokkaido (Ichiyanagi, et al., 2004; Watanabe, et al., 2006a; Figure 2). The distribution of micro-earthquake hypocenters has been also well defined for seismogenic zone to give much finer shape of the zone (Watanabe, et al., 2003; 2006b for example; Figure 3). Figure 3 depicts the distribution of micro-earthquakes that took place off Kushiro-Tokachi after the installation of the cabled observatory. Many of the events that may not be detectable only by land observations would, therefore, be detected around area where cabled observatories have been installed. Ichiyanagi, et al. (2004) noted that there was an earthquake swarm took place about two years before the 2003 Tokachi-oki earthquake (MJMA 8 subduction earthquake) near its hypocenter for two months. Although any causal relationship between the swarm and the mainshock of the M8 subduction earthquake, such short-duration swarm could not be well located or even detected without real-time telemetered cabled observation. We think that future installation of systems in the offshore would surely bring much deeper knowledge about seismogenic processes to researchers.

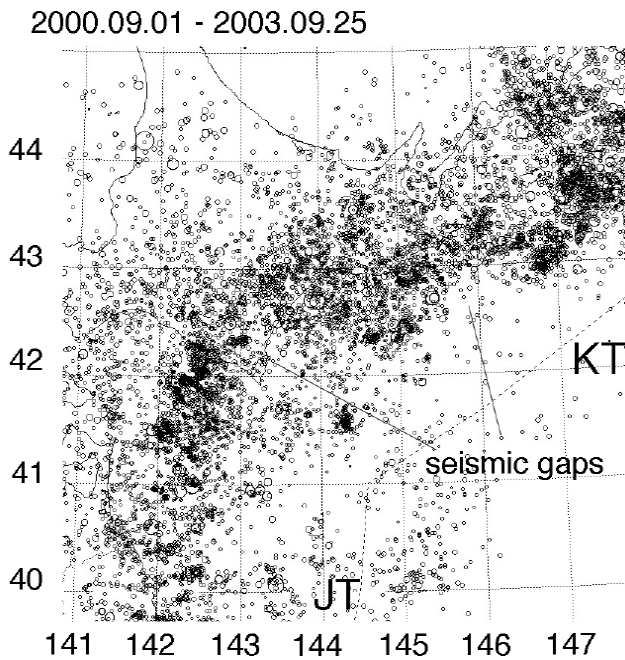


Figure 2 Epicenters of micro-earthquakes after the deployment of cabled observatory until a day before the 2003 Tokachi-oki earthquake (Watanabe, *et al.*, 2006). Earthquakes with magnitude greater than four are plotted in this figure. The epicenters of micro-earthquakes in the southwestern part of the Kuril seismogenic zone is almost uniformly distributed except for two seismic gaps off Nemuro Peninsula (right gap), and off Tokachi (left gap). The seismic gaps correspond to the focal areas of the 1973 Nemuro-Hanto-Oki (M_{JMA} 7.3) and 1952 Tokachi-oki earthquake (M_{JMA} 8.2), respectively. Notations, KT and JT, denote Kuril and Japan Trenches, respectively.

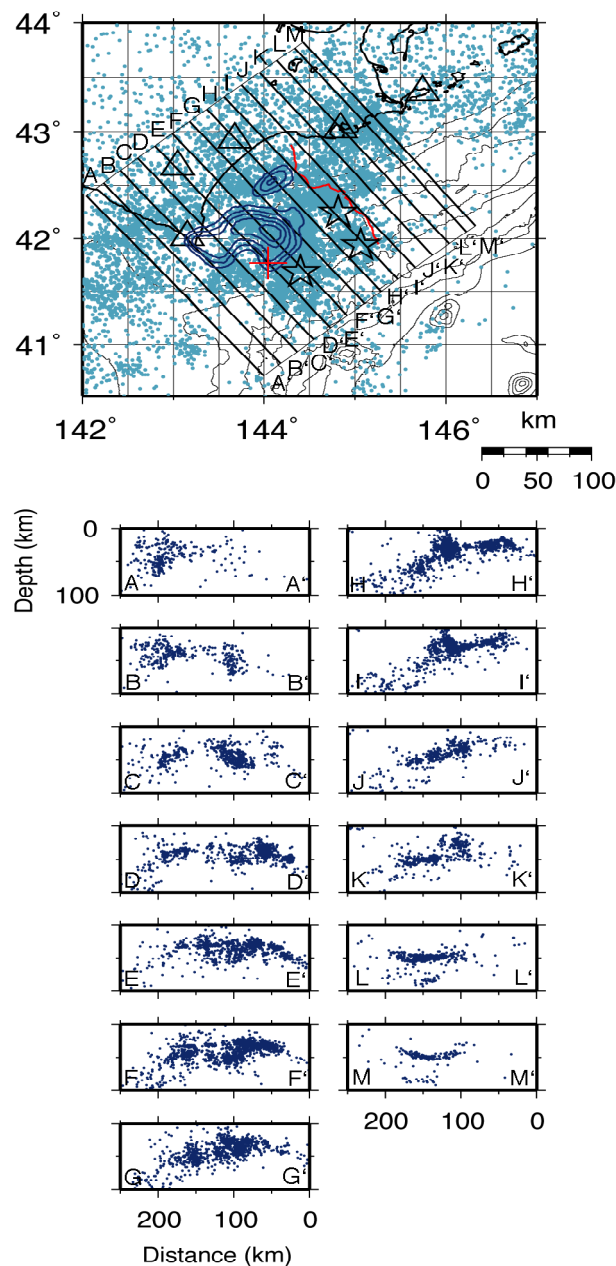


Figure 3 Epicenter and cross sectional hypocenter distributions after the 2003 Tokachi-oki earthquake (Watanabe, *et al.*, 2006b). Aftershocks were observed for a period from 26 September 2003 till 31 July 2005. Stars and Triangles in the top figure indicate locations of cabled ocean bottom seismometers (OBS) and land-based stations, respectively. Alphabetically aligned lines from A-A' to M-M' denotes sub-regions for each of which the depth distribution of hypocenters is drawn as shown in the bottom of the figure. Vertical exaggeration is taken as 1:1. Contour lines depict every one-meter displacement, i.e., the asperity map of the 2003 Tokachi-oki earthquake estimated by Yamanaka and Kikuchi (2003), on the plate interface. The maximum displacement is estimated greater than 5 meters. A red curve between two lines, H-H' and I-I', indicates the location of the Kuroshio Submarine Canyon. A red cross-hair indicates the epicenter of the 2003 Tokachi-oki earthquake.

Tsunami Studies

Pressure gauges attached to cabled observatories are run to detect tsunamis and underwater pressure fluctuations at the locations of the Japanese cabled observatories. Pressure gauges are, in general, have the resolution of, depending on the length of averaging window, about sub-millimeter at 1 Hz to lower frequencies. It was shown that the accommodation of tsunami data in the study of an earthquake has enabled us to constrain the depth of earthquakes in the offshore (Hirata, et al., 2003). Hirata, et al. (2003) proposed that observed tsunamis in the offshore could be compared with numerically simulated tsunami for the earthquake that caused the observed tsunami. Figure 4 shows the location of the earthquake that they used in their study. Since the source depth of the earthquake, which took place outside the available seismometer network, fluctuated depending on the choice of seismic velocity structure, it was difficult to estimate the depth with enough accuracy. On the other hand, the observed tsunami time series is a function of the order of deformation of the seafloor, which strongly depends on the fault parameters including the source depth, the source depth of the earthquake could be estimated through a generalized least square error criterion.

Matsumoto and Mikada (2005) have used an observed tsunami time series to constrain the fault orientation and inclination for an earthquake that took place near the toe of the Nankai trough. The hypocenter and the mechanism of the earthquake were well estimated in the land earthquake monitoring, but there was little aftershock after the mainshock. Due to the lack of aftershocks, a problem remained to identify which nodal plane could be the fault that had caused the earthquake. Matsumoto and Mikada (2005) compared two different numerically simulated tsunami time series for each of fault models with the tsunami observed by a cabled observatory about 100 km away from the shore, and found out the difference to conclude which nodal place should be the fault. At the same time, they found that the tsunami arrived about 20 minutes before it hits the shore nearest to the tsunami sensor of the cabled observatory (Figure 5). They claimed that this leading time of 20 minutes could be exploited for local habitant to evacuate and that it is fundamental to have real-time feature to cabled observatories in terms of tsunami disaster mitigation.

Mikada, et al. (2004) demonstrated that there was a standing pressure wave generated between the surface and seafloor at the time of the 2003 Tokachi-oki earthquake (Figure 6). When an earthquake deforms seafloor resulting in a static vertical displacement, a standing wave whose wavelength equals to four times the water depth could be generated. While tsunami height reflects the vertical displacement, the acoustic standing wave has amplitude almost proportional to a time derivative of the seafloor displacement, i.e., vertical deformation velocity. At the time of the 2003 Tokachi-oki earthquake, a pressure gauge installed ca. 28 km to the epicenter recorded both the tsunami and standing waves with the amplitudes of 0.4 and 40 meters, respectively, in equivalent water depths. Mikada, et al. (2004) concluded that the seafloor deformation took place in an interval of three seconds at the time of the earthquake and that proposed to deal with seafloor geodetic deformation as a function of time for future tsunami studies.

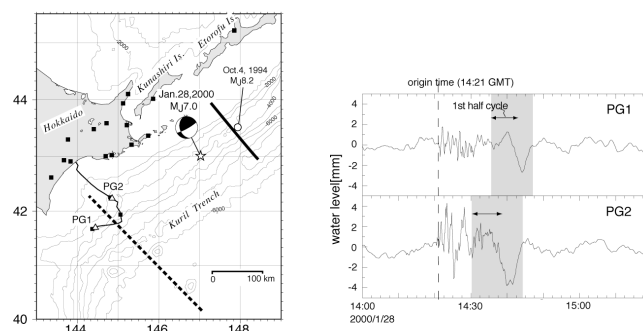


Figure 4 (Right) Location map of an earthquake (January 28, 2000) and the pressure gauges in the study by Hirata, *et al.* (2003). (Right) Observed water pressure at the locations, PG1 and PG2, which are indicated in the Figure (Left). The maximum

amplitude of the micro-tsunami was about 4 and 6 mm at PG1 and PG2, respectively. They estimated the depth of the earthquake, which is very difficult to determine by land seismic observations, to minimize the discrepancies between the observed and simulated tsunami waveforms within the first cycle of the onset. Both figures are reproduced from Hirata, *et al.* (2003).

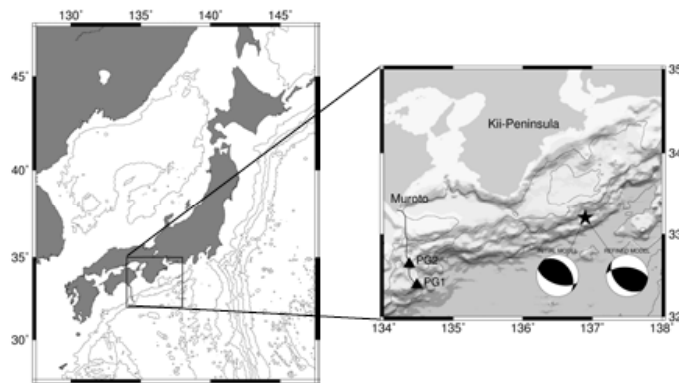


Figure 5 Location of the epicenter of the 2004 off Kii-Peninsula earthquakes (September 5, 2004; Matsumoto and Mikada, 2005). Star indicates the epicenter of both the fore- and the main-shocks. Triangles represent the locations of cabled pressure gauges off Muroto. Two focal mechanisms of the main-shock are estimated in a teleseismic waveform modeling by Yamanaka (2004). These two source models are slightly different from each other. The left one indicates a northeast-dipping fault, while the right southwest dipping. Although seismic waveform modeling cannot distinguish which is better due to a lack of aftershocks, tsunami modeling indicates that the southwest dipping fault model (right source model) is suitable to explain observed water pressures. Note that the tsunami was observed about 20 minutes before the arrival to Muroto tidal station, which is indicated in the figure.

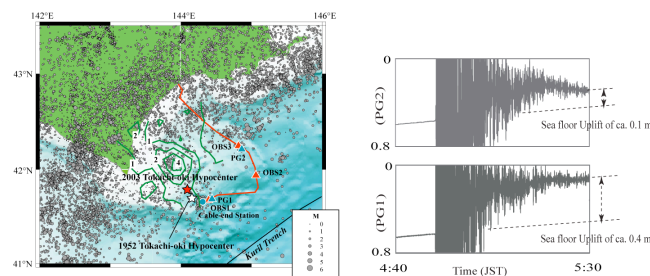


Figure 6 (Left) Locations of sensors in the region of the 2003 Tokachi-oki earthquake. Two open stars depict the hypocenter of the 2003 and 1952 Tokachi-oki earthquakes, respectively (Mikada, *et al.*, 2006). A thick line and triangles represent a cable and seismometer locations, respectively. A circle at the end of the thick line and triangles are for a cable-end station and tsunami gauge locations. Contours are drawn every meter for the displacements estimated by a joint inversion of teleseismic and strong ground motion data (Yagi, 2004) for the earthquake. Dark circles are for micro-seismic events since 2000 until August 2003 whose locations were determined by the Japan Meteorological Agency (JMA). Also the magnitudes of the events are indicated by the size of circles. (Right) Observed tidal record acquired by the cabled observatory at the time of the 2003 Tokachi-oki earthquake. Fluctuations in water pressure at the onset of the mainshock have the amplitudes about 40m in equivalent water depth at PG1, while about 30m for PG2. Static discontinuities at the two locations indicate the seafloor uplifts. High amplitude water pressure fluctuations were caused by abrupt seafloor uplift (Mikada, *et al.*, 2004). Tsunami is also included in the tide record whose half amplitudes were about the same as the seafloor uplift values (Mikada, *et al.*, 2004). They are all superimposed in the fluctuations.

Geodetic Studies

The 2003 Tokachi-oki earthquake took place near a cabled observatory. After the main shock, water pressure data from the tidal gauges in the observatory showed a linear trend in the difference between the synthetic and observed water depths. The rates of the linear uplifts at the pressure sensor locations are estimated as 4.1 and 3.9 mm/day respectively at the PG1 and PG2 locations over a period of two months after the mainshock (Mikada, et al., 2006). After the main shock, the fluctuation of the difference between the observed and estimated water pressures became unstable and the uplift of the seafloor continued.

One of the observatories at the time of the 2003 Tokachi-oki earthquake was the coseismic uplift of the seafloor. If we estimate the distribution of seafloor uplift using one of the rupture models obtained by seismic waveform studies, the recorded static uplift can be well explained as shown in Figure 6. In Figure 7, we could see that the major part of coseismic deformation is located in the offshore and that there is a tendency in the distribution of aftershocks to be located beneath the uplifted zone of the rupture area.

Long-term variations also indicate that preseismic subsidence and postseismic uplift took place in before and after the mainshock. These pressure fluctuations are now recognized as a preseismic seafloor subsidence and postseismic seafloor uplift before and after the earthquake, respectively. The cabled observatory was installed in 1999, i.e., four years before the mainshock, and pressure gauge data recorded about 3 cm/yr of the continuous subsidence of the seafloor before the mainshock (Mikada, et al., 2006). After the mainshock, a continuous uplift was observed at a rate of 4 mm/day at the beginning and the rate of uplift asymptotically diminishing in a year term. These long-term variations are, however, not confirmed in the reliability, since the long-term response changes of the pressure sensors have not been well analyzed in the past. As Takahashi and Kasahara (2003) pointed out that preseismic changes such as the formation of a seismic gap before the 2003 Tokachi-oki earthquake, there should be certain processes on-going in the focal region of the earthquake. However, sensors of the above long-term passive monitoring system could not detect any change other than that of seismicity or long-term seafloor subsidence. This fact implies three major future directions: (i) observations should be made as closer as possible to the hypocenter of plate boundary earthquakes to detect signals with a good signal-to-noise ratio, (ii) improvement of our understanding of seismogenic processes enough to model the nucleation of earthquakes, and (iii) introduction of active schemes to monitor seismogenic processes at depth.

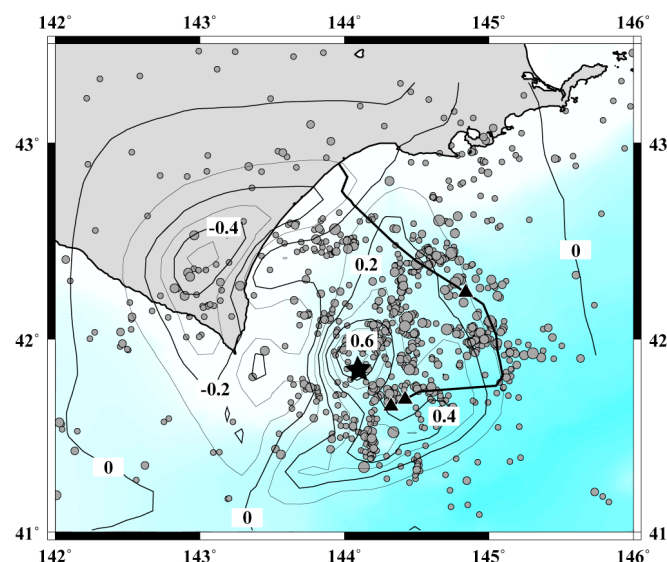


Figure 7 Estimated coseismic uplift at the time of the 2003 Tokachi-oki earthquake (Mikada, et al., 2006). Because of

displacement distribution for the plate boundary, large area of vertical displacement is formed mainly in the offshore and relatively minor subsidence takes place along the coastline. The numbers on the contours are in meter and solid circles are for post-seismic events whose estimated magnitudes are more than three. Unit of the vertical displacement values is meter.

ADVANCES IN ASPERITY STUDY

It has been hypothesized that the source regions for plate boundary earthquakes have localized stronger mechanical coupling, i.e., asperities (Kanamori and Stewart, 1978), along plate boundaries. The 2003 Tokachi-oki earthquake took place 51 years after the 1952 Tokachi-oki earthquake has shown that not only the hypocenter location but the asperity distribution are very similar to each other (Yamanaka and Kikuchi, 2003). Recently, the study of earthquake source mechanisms have revealed that the location of asperities seems fixed in space away from hypocenter, i.e., the location of initial breaks, and is a region of low aftershock activity after the asperities have ruptured for seismogenic zones in the northeastern Japan for the past 70 years (Yamanaka and Kikuchi, 2004; Figure 8). These findings indicate that a spatial distribution of asperities, is closely related to seismic radiation of possible future plate boundary earthquakes. If we assume that the asperities are space invariant during at least several tens of years, we might be able to map asperities, which are strongly related to mechanical coupling, along the plate interfaces.

Fujie, et al. (2002) found that there are strong reflections from a plate interface, on east off Tohoku along Japan Trench subduction zone, in their seismic reflection profiling and that the strong reflections could be mapped onto the plate interface of low seismicity of micro-earthquakes, i.e., aseismic regions. They suggested an existence of materials with low compressional wave velocities along the plate interface to explain the observed amplitudes of seismic signals. Mochizuki, et al. (2005) used data from Fujie, et al. (2002) and concluded that the aseismic regions could be caused by fluids and clays produced from sediments, which are subducting with the plate. They also proposed that aseismic slips would be dominant along the plate interfaces of observed strong seismic reflections (Figure 9). In this regard, we may assume that what Mochizuki, et al. (2005) proposed, can imply mapping of non-asperity regions. If we compare the results from the above studies (Figures 8 and 9) which were obtained for the same areas with different spatial scales, than we see that there is less overlap between the asperities (Figure 8) and the strong reflections (Figure 9) in an area near the 39°N and 143°E. The strong reflections found by Fujie, et al. (2002), seem to surround the asperity of the 1968A earthquake (Figure 8). Since the spatial scale of these two studies are so different, this interpretation is not deterministic, but we could guess that at least non-asperities could be mapped with help of active surveys, such as seismic reflection profiling.

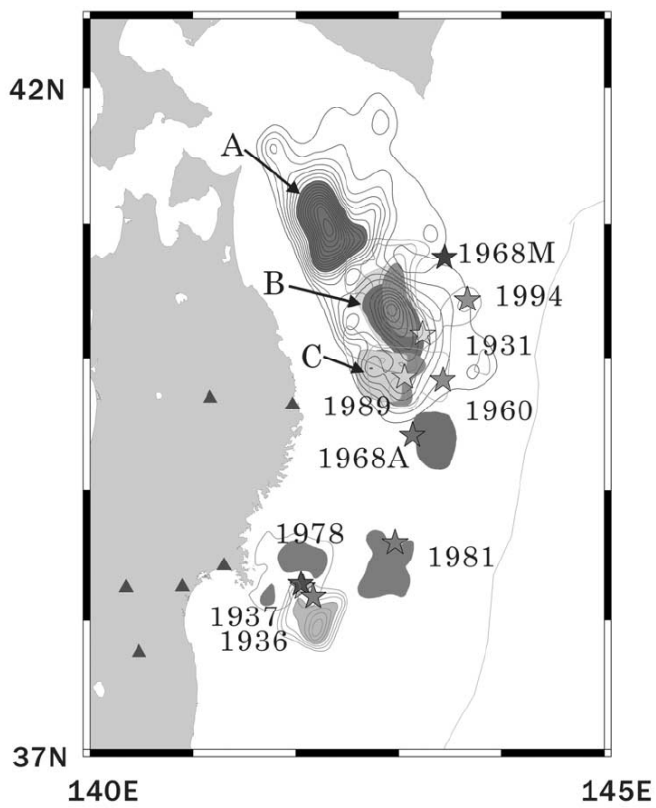


Figure 8 Asperity map for major plate boundary earthquakes, Off Tohoku, northeastern Japan, derived from teleseismic waveform modeling by Yamanaka and Kikuchi (2004). Stars indicate the locations of the initial ruptures. Contour lines show the moment release distribution for every 0.5 meters. Areas within the value of half the maximum slip for each seismic event are shaded as asperities.

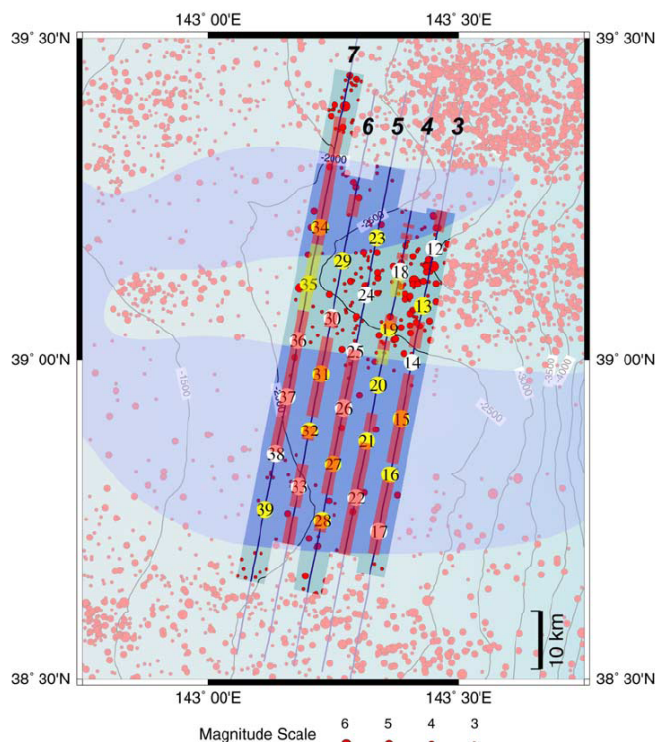


Figure 9 Map showing the difference in reflection coefficients for the plate interface (Mochizuki, *et al.*, 2005). Numbered circles are locations of OBSs used in this study. Non-numbered solid circles are epicenters of earthquakes with magnitudes greater than 2.5 observed by on-land seismic network of Tohoku University during a period from 1975 to 2002. Two distinctive aseismic regions are seen for an area from 38°42'N to 39°00' and from 39°06'N to 39°18'N. Seismically active area on the top-right of the figure is a part of asperities shown in Figure 8. This figure indicates that reflection amplitudes in seismic reflection profiling could map aseismic regions.

EXERTION OF EARTHQUAKE MONITORING CAPABILITY

It would be right to say that any earthquake-related phenomena are observable if and only if they are associated with dynamic changes in environmental physical parameters, i.e., water pressure change, oscillation, etc., in the system of inertia. Earthquake models generally use static values of pore pressure to explain that interstitial fluids support the load between two fault planes (Brodsky and Kanamori, 2001). Seismologists think that pore fluids play an important role in the generation of earthquakes both to lower friction at the interface of two materials facing each other in fault zones, and to reduce normal load to the fault plane (Hubbert and Rubey, 1959). The importance of hydrological observations or the detection of changes in physical properties in fault zones is, therefore, claimed. Unfortunately, there are not so many observations that have been done for monitoring fluid pressures except for off-line systems such as Circulation Obviation Retrofit Kits (called as CORK; Davis, *et al.*, 2004 for example). Since passive monitoring of such properties at depth require drilling or any other schemes to enable direct accesses for installing sensors or observation systems.

Physical properties of materials in fault zones may be manifested in earthquake behavior along the subduction zone interface (Bilek and Lay, 1998). Tsuru, *et al.* (2005) conducted a time-lapse seismic reflection survey before and after the 2003 Tokachi-oki earthquake and found that reflection coefficients of some reflectors near the source area exhibited a spatiotemporal evolution. They used the evolution pattern and the aftershock observations of Shinohara, *et al.* (2004), and proposed that the change is caused by gradual fluid flow. The magnitude of the reflectivity change implies a 1.6% increase in porosity, a 2.2–5.6 MPa reduction in shear strength under the condition of the

subsequent permeability in the plate boundary shear zone to be 10-15 mD. Tsuru, et al. (2005) have shown that a time-lapse seismic survey can be applied to detect changes in physical properties for inter-plate earthquakes.

Ma, et al. (2003) analyzed ground motion data of the 1999 Chi-Chi earthquake in Taiwan and found that a fault lubrication mechanism can be applied to the explanation of the difference in the frequency contents of seismographs between the two regions near the earthquake fault. They also proposed that fluid pressure in the fault zone with respect to the order of asperity defines the slips in the fault zone and the frequency contents of the radiations.

If we interpret the above findings, the following necessary conditions could be summarized towards monitoring of earthquake fault for future rupture:

- (1) Mapping of the order of asperity over the fault plane is necessary to know where possible large slips are likely to take place,
- (2) Fluid pressure distribution at fault interface needs to be estimated with respect to the distribution of asperity, and
- (3) A time-lapse reflection profiling would contribute to estimate large changes in physical properties in seismogenic zone before and after an inter-plate earthquake.

Therefore, it would be fair to say that a future observation and monitoring require both space and time axes to understand earthquake phenomena.

DISCUSSIONS

Passive Monitoring of Seismogenic Processes

In the previous chapters, we listed the scientific results from passive monitoring. Since cabled observatories are deployed near or right above the seismogenic zones, the acquired data from the cabled observatories could bring new findings in geodesy, seismology, tsunami disaster mitigations, etc. Tsunami observation has proven that it is important to have additional data to constrain fault parameters or to monitor geodetic seafloor movement as a function of time (Mikada, et al., 2004). Offshore tsunami observation detected tsunamis with enough leading time to the arrival to the shore (Matsumoto and Mikada, 2005). Seismic records have shown that the spatial coverage by sensors over a wide focal plane of earthquakes enhances the resolution in the hypocenter determination (Shinohara, et al., 2004). Multidisciplinary seafloor environment sensors have worked to detect underwater debris flow associated with an inter-plate boundary earthquake (Mikada, et al., 2006). In these past studies, it has been proven that the data obtained using cabled observatories are indispensable to understand the nature of earthquakes in terms of disaster mitigation, understanding their generation mechanisms, etc.

Since the deployment of cabled observatories is always associated with the difficulties in funding, the number of observatories that has been installed is limited. However, we need to exert our efforts to improve the situation by means of increasing the number of sensors to enhance the spatial coverage near plate boundaries for further understanding of generation of earthquakes at plate boundaries. In terms of disaster mitigation, real-time observations should be realized and the installation of cabled systems is the most practical solution.

We are now working towards the next step in understanding of earthquakes, and should consider the observation systems reflecting the past experience. We learnt that tsunami generation process is related to the velocity of geodetic seafloor movement and that turbidity current is a phenomenon associated with an earthquake. Multi-disciplinary observation would be one of examples that necessitate any other means as part of cabled observations so that the earthquake related phenomena including those unknown in the past are to be detected and analyzed together with seismogenic processes.

Active Monitoring

A time-lapse reflection survey has been proven to be an important scheme to acquire any changes in physical properties near fault interface for which asperity is mapped as a function of space through the reflection profiling technique (Fujie, et al., 2002; Sato, et al., 2005; for example). As Tsuru, et al. (2005) attempted, the method should lead to monitoring of variation of fault zone properties after steady efforts of signal-to-noise enhancement for reflections in acquired data.

Tsuru, et al. (2005) assumed continuous fluid flow for 3.4 years to explain the difference in reflection coefficient of a reflector before and after the 2003 Tokachi-oki inter-plate earthquake as alluded in the above. The reflection coefficient for the subsequent survey has become 2.7 times that for the initial survey. Since it is not possible to see if any expulsion of fluid took place at the inter-plate earthquake, a continuous fluid flow was the only possible assumption to explain the changes in reflection coefficient. However, as already reported by many authors, the combination of both steady and intermittent fluid flow seems to be a solution explaining the observed permeability and geochemical state of sediments and décollement at least at three subduction zones, i.e., Nankai, Costa Rica, and Barbados (Moore and Silver, 2002). Seismological advances now require continuous monitoring of such properties to understand how these changes take place in time. For these objectives of acquiring changes physical properties, active monitoring schemes including not only seismic reflection profiling but also the development of high-precision methodologies to detect such changes at depth are indispensable.

The inclusion of Space-Time Axes in Observations

Most of plate boundary inter-plate boundary earthquakes take place in the offshore. Major crustal deformations take place, accordingly, in the offshore. Although high density seismological and geodetic observations are now possible on land, we would like to emphasize that long-term and high precision measurements or observations in the offshore would be one of the most important directions for detecting any changes related to generation of subduction-related earthquakes, i.e., seismogenic and inter-seismic processes, at much closer locations to seismogenic zone. Also, the inclusion of observations to detect any time-dependent changes of physical properties in the vicinity of seismogenic zones is the most indispensable scheme for a break-through in the present seismology. Any interstitial fluid flow near earthquake fault would change pore pressure in time and space. Changes in physical properties might, accordingly, be not only time-dependent but space-dependent, too. We believe that the current technology of cabled observatory or any offshore observational schemes should be enhanced to accommodate any future extension of observations in terms of precision and detectability for changes of physical properties near earthquake fault both in space and time. Moreover, methodologies need to be developed to bring information on physical properties from the deep earthquake fault in a form of detectable signals. We think that active monitoring is one of the feasible directions towards the ultimate objectives of understanding earthquake phenomena. Figure 10 depicts a proposed direction called the Exploration of Asperities-Reflectors System (EARS; Tsuruga, et al., 2006) for integrating the-above-mentioned mapping, monitoring, and real-time continuous monitoring of the seismic activity in seismogenic zones.

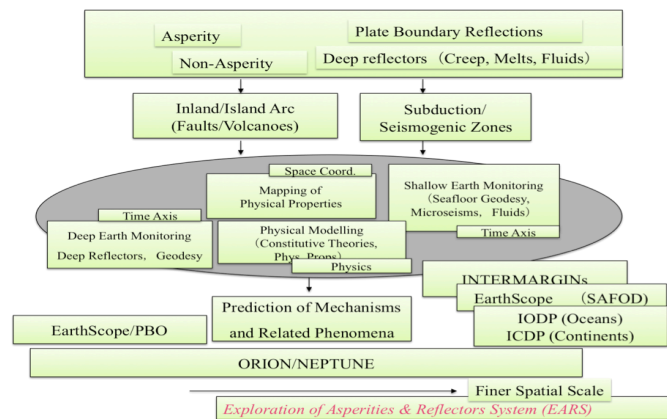


Figure 10: Schematic conceptual diagram of the Exploration of Asperities-Reflectors System (EARS; Tsuruga, *et al.*, 2006). As discussed in the text, we think that it is fundamental to understand earthquake generation as a function of time and space. Since any researches may be aliased either in space or in time, allied efforts to integrate all available products are essential to cover variation of wide spectra. In particular, long-term monitoring by cabled observatories, mapping of physical properties by active source surveys, and monitoring of time-varying physical properties are indispensable tools.

CONCLUSIONS

We have summarized the scientific achievement using data from Off Kuroshio Tokachi cabled observatory. Introducing recent advances in earthquake seismology such as earthquake asperities, time-lapse reflection profiling, etc., we would like to mention that it is very important to have the observatories in the offshore. Our conclusions are as the following:

- (1) A real-time cabled observatory has shown the ability:
 - (i) to improve the accuracy of hypocenter determination and, hence, our understanding of tectonics through the spatial variation of aftershock seismicity,
 - (ii) to highlight the importance of temporal geodetic changes in the generation of tsunami, and
 - (iii) to detect tsunami with long-leading time to the arrival at the shore,
- (2) Mapping of physical properties along an earthquake fault plane is necessary for future understanding of earthquake generation, and
- (3) Development of active monitoring schemes is of importance to detect spatiotemporal changes in physical properties along the earthquake fault.

We all know that one of the best ways to take, would be the deployment of cabled observatories for detection and the development of active sources which have ability to radiate signals to bring any information on changes of physical properties at depth back to the cabled observatory.

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